

EXPERIMENTAL STUDY OF TOPOGRAPHIC EFFECTS USING EXPLOSIONS AND MICROTREMORS RECORDINGS

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ABSTRACT

A field experiment for the study of ground motion variation across a topographic relief, based on explosions and microtremors recordings, was carried out. The hill selected for the experiment is located in Northern Greece, close to the Lagada lake, about 15 km NW of the Euroseistest experimental test site. It is constituted by quite homogeneous metamorphic rocks. The experiment consisted in the execution of four explosions at the toe of the hill. Ground motion was recorded at the crest, at the toe and along the flanks. Between explosions, data acquisition at the crest proceeded continuously to record ambient noise. The explosion data were used to construct experimental seismic sections to study the scattered wavefield. They also were processed using standard spectral ratios (SSR) between the station at the crest and those at the toe and along the flanks showing topographic relative amplification between these points. In addition, horizontal to vertical spectral ratios (HVSR) were also computed both using explosion data and ambient noise recordings in order to explore the applicability of this non-reference technique in estimating topographic effects. Finally, experimental HVSR at crest were compared with those obtained from numerical modeling with a bidimensional boundary element code showing a good agreement at least in terms of spectral shape.

Keywords: topographic site effects, explosions, microtremors, standard spectral ratio (SSR) technique, horizontal to vertical spectral ratio (HVSR) technique.

INTRODUCTION

Numerous observations after strong earthquakes have shown that the effects of local topography on ground motion can be very important. Both numerical and experimental studies show that the ground motion at ridge crest is amplified with respect to the toe and this amplification is maximum in the frequency range corresponding to wavelengths comparable with ridge width. If the basic physical phenomena responsible for topographic site effects are satisfactorily understood, a quantitative disagreement between theoretical predictions and experimental amplifications is observed, the latter being generally much higher (Bard and Riepl-Thomas, 1999; Pitilakis, 2004). The experimental evaluation of topographic amplification is difficult because it depends from many factors among

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which the difficulty of finding an adequate reference station and the coupling between the effects of the “stratigraphy” (i.e. impedance contrast due to subsoil mechanical heterogeneity) and of the “topography”. A recent review of the available numerical and experimental studies on topographic effects can be found in Pagliaroli (2006). The effects of topography have been widely studied by several analytical and numerical methods while, conversely, instrumental evidences of topography effects are relatively few. Experiments performed for the investigation of site effects are very costly since they require the maintenance of the instrumentation for a long time to acquire strong motion records. For this reason, despite their theoretical limitations, explosions and microtremors data can be very useful to estimate site effects experimentally.

In this paper the results obtained by a field experiment for the study of ground motion variation across a topographic relief, based on explosions and microtremors data, is presented. The experiment consisted in the execution of four explosions at the toe of the hill. The resulting ground motion was recorded at the crest, at the toe, and along the flanks of the hill. Between explosion data acquisition at crest proceeded continuously in order to record ambient noise. The aim of the experiment was twofold: to study the scattered wave-field and to evaluate the ground motion variations across the hill profile.

Most studies have characterized the amplification due to topography using standard spectral ratios (SSR) at various points on a topographic features. However, these estimates require an adequate reference station, i.e. located on an unweathered and flat outcropping bedrock. A site with these characteristics is extremely difficult to find during a field experiment. For this reason, non-reference techniques, such as horizontal to vertical spectral ratios (HVSr), have received an increasing attention. The HVSr technique has been applied both on earthquake and microtremors (Nakamura's estimate) data. Many studies have been conducted to estimate site effects at sedimentary sites using HVSr (Lermo and Chávez-García, 1993; Bard and Riepl-Thomas, 1999). However, only in a few cases has this technique been extended to topographic effects evaluation (Chávez-García et al. 1996, 1997; Zaslavsky and Shapira, 2003). Chávez-García et al. (1996) found a good agreement between HVSr computed from weak-motion data and those calculated on microtremors. Moreover, they compared experimental HVSr with those obtained by numerical modeling, concluding that topographic effects may be detected using this technique. However, the windows for computation of HVSr of microtremors were too short (4-5 seconds of pre-event noise), therefore the Authors themselves suggest that these results should be further substantiated. Encouraging results were also obtained by Zaslavsky and Shapira (2003) who found a good qualitative and quantitative agreement between HVSr estimated on S wave windows of weak-motion data (receiver functions) and HVSr computed on ambient noise. In this study, experimental data were first processed using SSR between the station at crest and those at the toe and along the flanks. As no adequate reference station was available, the applicability of the very attractive and inexpensive HVSr technique was checked. The horizontal to vertical spectral ratios, computed from both explosions and microtremors data, were finally compared with HVSr estimated by 2D numerical analyses of site effects of the studied hill.

SITE DESCRIPTION

The site selected for the experiment is a rocky hill located close to the Lagada lake, about 30 km NE of Thessaloniki in Northern Greece (Figure 1a). The hill is only a few kilometers away from the sedimentary valley of Volvi graben in which the EUROSEISTEST instrumented test site (<http://euroseis.civil.auth.gr/>) is located (Raptakis et al, 2000; Chávez-García et al., 2000). Euroseistest is a natural scale laboratory for the investigation of open issues in earthquake engineering and engineering seismology. A large amount of research has been undertaken there during recent years and has involved a large number of universities and specialists in Europe (Jongmans et al., 1998; Riepl et al., 1998; Marrara and Suhadolc, 2001 among others). The area is located in the Serbomacedonian massif which is a seismotectonically active region with a rather high seismicity; the largest earthquakes in this area during the last century were those of Kresna $M = 7.4$ in 1904, Ierissos $M = 7.2$ in 1932 and Volvi $M = 6.5$ in 1978.

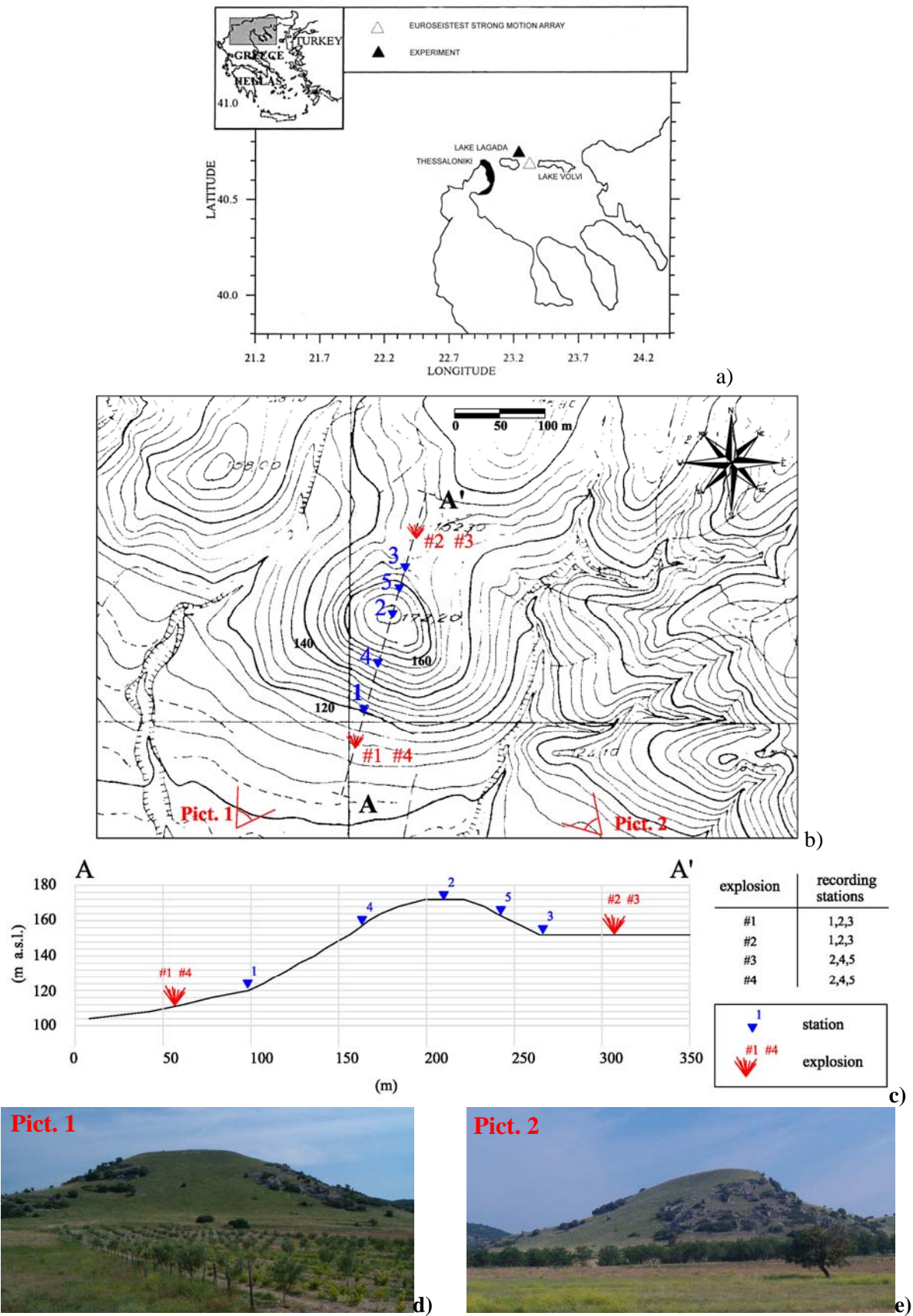


Figure 1. Location of the studied area (a); topographic map (b) and cross-section A-A' (c) of the hill with the location of explosions and recording stations; in the bottom part two pictures taken from the SW (d) and from the SE (e) are also shown.

The hill is about 150 m wide at the base and its average height is 40 m. It is constituted by quite homogeneous metamorphic rocks, mainly schist and gneiss similar to rocks forming the Volvi graben bedrock. The topographic map and the cross section A-A' of the hill are shown in Figure 1b and 1c respectively. Two pictures of the hill taken from the South-West and from the South-East are also shown in Figure 1d and 1e respectively. It can be noted that the hill has a tridimensional and asymmetric geometry, with a height of 20 m, when seen from the North, and of 50 m, when viewed from the South. The aspect ratio h/l of the upper part of the hill is about 0.4, where h is its average height and l its half-width. Metamorphic rocks outcrop widely on the hill and the adjacent topographic features, while a significant sediment cover can be found at the Southern toe with thickness increasing as we move closer to the Lagada Lake.

DATA ACQUISITION AND PROCESSING

The field experiment consisted of executing four explosions at the base of the hill and recording ground motion along the cross section A-A'. Between the explosions, data acquisition continued to record ambient noise (microtremors). The recording instruments were three units of three-component broadband seismometers GURALP CMG-40T, with passing frequency band from 0.33 to 50 Hz. The signals from GURALP sensors were recorded by three REFTEK type DAS-130 digitizers each of which was connected with a GPS unit. The explosions were produced with about 400 g of plastic explosive located in one-meter deep holes. Two explosions (#1 and #4) were executed from the Southern side and two (#2 and #3) from the Northern one, as shown in the map of Figure 1b. In the same figure the location of the recording stations along the hill is illustrated. The seismograph at the crest (2) was kept fixed while the other two stations were installed at the toe (station 1 and 3) during explosions #1 and #2 and moved upward along the flanks (stations 4 and 5) for explosions #3 and #4. The stations recording each explosion are summarized in the table included in Figure 1.

Typical data obtained from explosions are shown in Figure 2. In this figure, vertical, NS and EW components of ground motion recorded at the station 2, 4 and 5 during explosion #3 are shown. It can be observed that we obtain significant amplitude of ground motion only for a duration of 0.2-0.4 seconds. For this reason, only frequencies higher than 5 Hz can be considered. The amplitude of ground motion decreases strongly with distance from the explosion. The distance between the stations is comparable with the distance from the source. Thus, the differences in ground motion amplitude observed in the different stations are due to both path and site effects. This is a crucial issue to be considered in data processing if a technique requiring a reference site is employed (such as SSR). One possible approach to try to isolate site effects from path effects is to consider explicitly a correction for geometric attenuation in the SSR as shown in the following. Ground motion records at the surface include "information" from the three factors that govern earthquake (or explosion) ground motion: the source mechanism, the propagation path of seismic energy and the effect of local geology and topography on the wave-field at the recording site. Therefore, in the frequency domain, the amplitude of motion at a selected station i during event j can be written with the form of a product (Borcherdt, 1970):

$$R_{ij}(f) = E_j(f) * P_{ij}(f) * S_i(f) \quad (1)$$

where E_j represents the source, P_{ij} characterizes the propagation from the source to the site and S_i expresses the effect of local soil conditions and topography. For a given event ($E_j = \text{constant}$) and assuming $P_{ij} = 1/r_i$ where r_i is the source-to-site distance (i.e., assuming propagation of body waves), the spectral amplification A due to site effects measured at the station i with respect to the reference site 0 can be written as:

$$A(f) = \frac{S_i(f)}{S_0(f)} = \frac{R_i(f)}{R_0(f)} * \frac{r_i}{r_0} \quad (2)$$

The expression (2) shows that the amplification A is the classical SSR corrected by the simple ratio, r_i/r_0 , between the distances of each station to the source. This procedure is a rough approximation since the explosion produces a very complex signal characterized by both surface and body waves.

Spectral ratios were computed as follows. First, a time window of about 3-sec duration was chosen around the largest amplitudes of the seismograms corresponding to the explosions. The traces had their linear trend and mean value removed, and horizontal components were rotated to obtain radial and transversal components relative to section A-A'. The waveforms were then band-pass filtered between 3 and 30 Hz. These windows were Fourier transformed and their amplitude was smoothed with a moving Hanning window of width 0.7 Hz. The smoothed amplitude spectra were used to compute spectral ratio between the crest and all the other stations according to expression (2). This SSR, corrected for geometric expansion, was finally smoothed again with the same moving Hanning window. The same procedure was used to compute the horizontal to vertical spectral ratios (HVSR) at each station from explosions data. The HVSR for microtremors were computed as follows. From the continuous ambient noise records, we selected more than one hundred 40-sec long time windows, with 10-sec overlap. All the waveforms were band-pass filtered between 0.5 and 30 Hz, and horizontal components were rotated to obtain radial and transversal components relative to section A-A'. The total length of ambient noise analyzed was about one hour. Fourier amplitude spectra were again smoothed with the same running Hanning window, and the spectral ratios between horizontal relative to vertical components computed for all the sites. Finally, the HVSR themselves were smoothed with the running Hanning window. We observed a good stability among HVSR computed from the different time windows, and only a few ratios were rejected for the computation of average values. Data processing was carried out by using SAC (Goldstein et al., 2003).

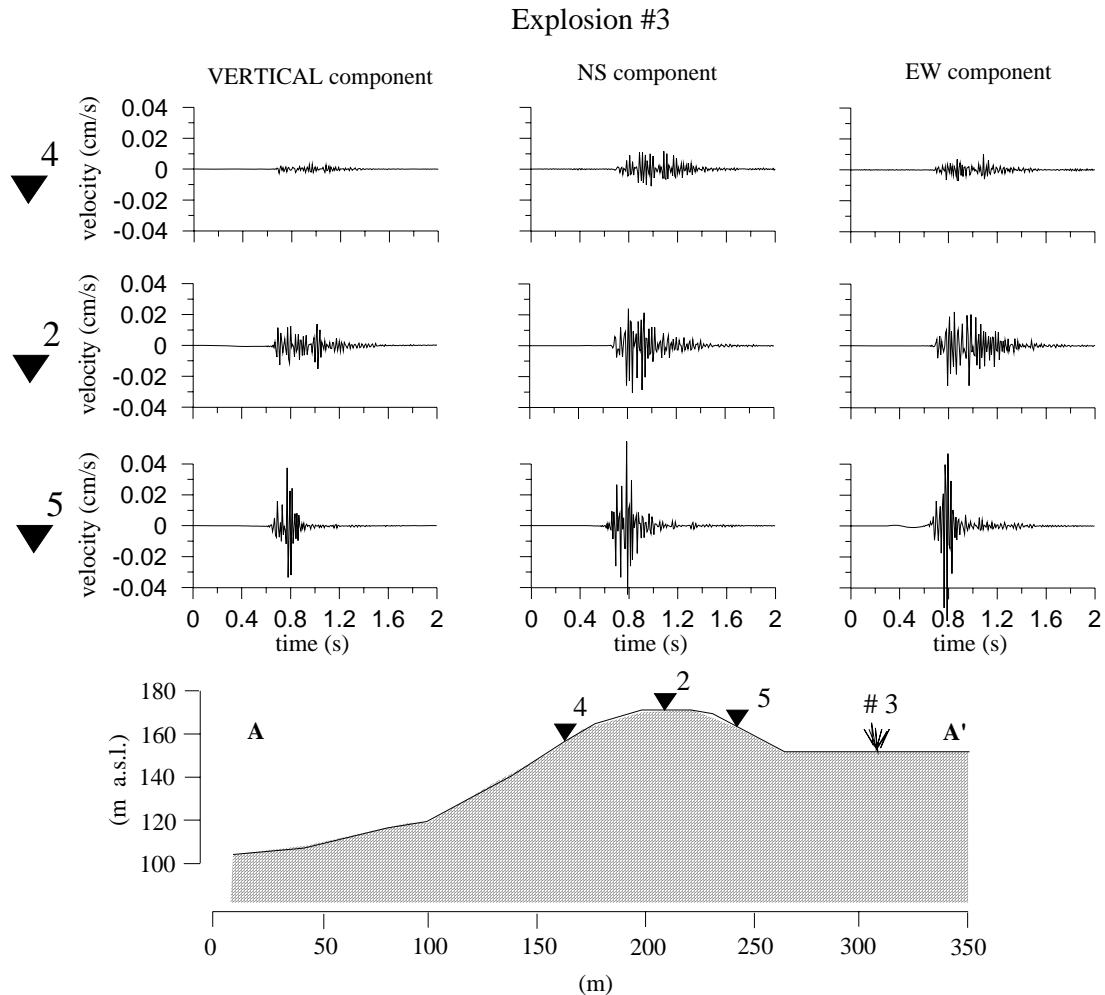


Figure 2. Time histories of the vertical, NS and EW components recorded at the stations 2, 4 and 5 during explosion #3.

EXPERIMENTAL RESULTS

Seismic section along the hill

In order to study the wavefield scattered by the topographic feature, experimental seismic sections along the hill were constructed. In Figure 3 the seismograms of vertical and radial component recorded along the hill during explosions #2 and #3 are reported. Recordings from the two explosions are displayed together since very similar time histories were observed at the crest for the two events. The signals were low-pass filtered with a corner frequency of 20 Hz to facilitate the identification of the different waves. Each signal was scaled to its maximum in order to be able to compare the shape of the traces, as we will not deal with a quantitative analysis. The wavefield generated by superficial explosions can be quite complex and include both body and surface waves. The first arrival at all the stations can easily be identified as P-waves, followed by SV-waves. In the two stations 3 and 5, located close to the source, it is not possible to separate the different waves generated by the explosions. In contrast, in the record obtained at the crest, a group of Rayleigh waves (denoted as Rayleigh waves 1 in Figure 3) appears after body waves arrival, moving downhill. At station 1, another surface wave group was identified at the end of seismograms (Rayleigh waves 2). The duration of ground motion increases significantly due to the appearance of these two groups of Rayleigh waves. Surface waves diffracted by ridges have been identified in other experimental works such as the Sourpi array (Pedersen et al., 1994), where emission of diffracted waves propagating from the top toward the base of the ridge was observed.

The measured group velocity of Rayleigh waves is about 1000 m/s. A similar value was attributed to shear wave velocity of the weathered schist in the geotechnical model of the adjacent Volvi graben valley (Raptakis et al., 2000). The measurement of this wave propagation velocity allows to estimate the shear modulus of the materials forming the hill. This parameter will be used to model the dynamic response of this topographic feature, as it will be shown later.

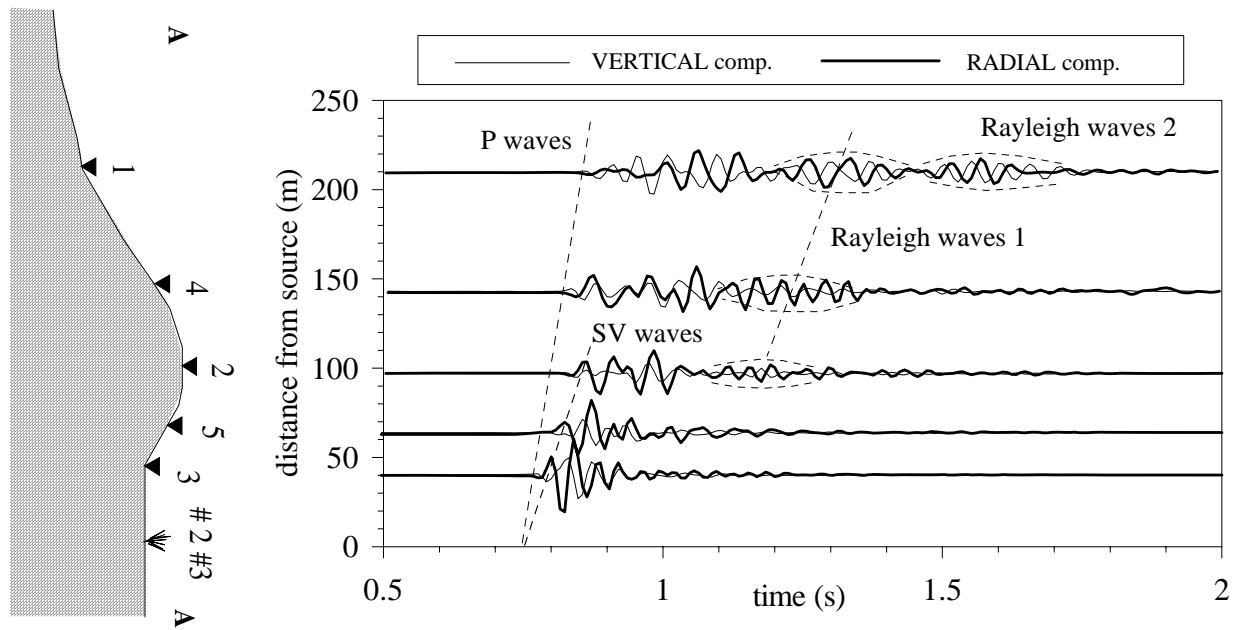


Figure 3. Filtered seismograms of vertical and radial components recorded along the hill during explosions #2 and #3.

Standard Spectral Ratio (SSR) technique

The spectral ratios between the station at the crest and the other stations located at the toe and along the flanks of the hill are shown in Figure 4 for explosions #2 and #3, in the frequency range from 5 to 25 Hz. The average SSR is also shown. SSR were computed according to (2) to roughly take into account the effect of the geometric attenuation on ground motion amplitude. Assuming a value of 75

m for the half-width l of the hill, and 1000 m/s for the shear wave velocity, we can compute the dimensionless frequency:

$$\eta = \frac{\omega l}{\pi V_s} \quad (3)$$

In our case, the values of the dimensionless frequency lie between 0.75 and 3.8. It is within this range that topography effects can be expected to be largest since this range corresponds to wavelength comparable to hill width. It should be noted that the SSR we computed cannot be considered an absolute estimate of topographic amplification. The reason is, of course, that all the reference stations we used are themselves affected by the presence of the hill. The stations along the flanks are certainly influenced by the topography, while those at the toe (especially station 1) are probably affected not only by the topography, but also by the presence of a non-negligible thickness of loose material overlying the schists. In the studied area, it is almost impossible to find a good reference station for SSR estimates, i.e. a flat rock outcrop. The relatively flat area to the South is covered by alluvial and detrital sediments. To the North, East and West, the studied hill is surrounded by other hills with similar shapes. For this reason, the SSR peaks can be interpreted both as amplification at the crest and deamplification at the “reference” sites. We observe in Figure 4 that the SSR computed for the vertical and radial components are more stable than those computed for the transversal component. Moreover the vertical component SSR shows less variations and smaller amplification than SSR for the horizontal components, at least for frequencies smaller than 20 Hz. Average relative amplifications are generally smaller than 5. With regard to the average SSR for radial component at the crest, we can identify three amplification peaks. The first occurs at a frequency smaller than 10 Hz. The second occurs in the range 14-19 Hz, and the last one at a frequency around 23 Hz. A clear deamplification peak appears around 21 Hz.

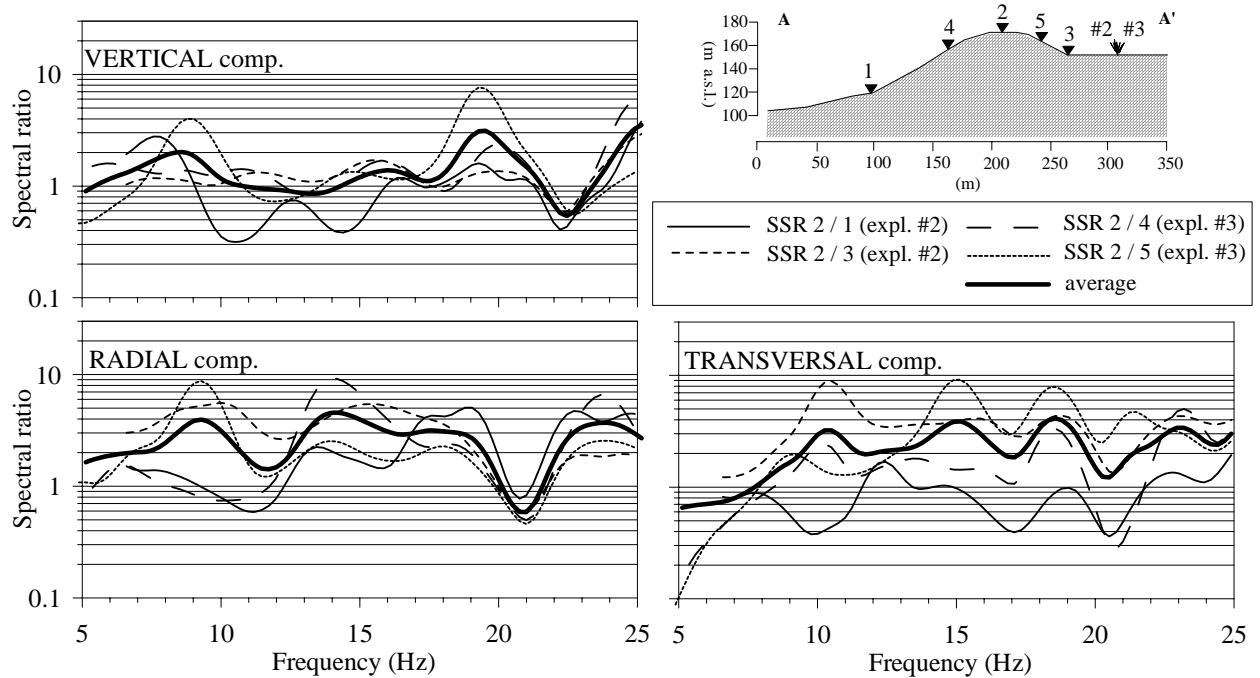


Figure 4. “Corrected” SSR for the vertical, radial and transversal components computed from explosions #2 and #3; the ratios shown are for station at the crest with respect to the others.

Horizontal to Vertical Spectral Ratio (HVSr) technique

HVSr computed from explosions

As mentioned above, HVSr were computed using the same time windows employed for SSR computations. Figure 5 shows HVSr computed for both the horizontal components recorded at the crest (station 2) and those recorded at the Southern toe (station 1). For comparison, average SSR at the crest is also reported. At the toe, the HVSr shows a good agreement in shape between the two explosions, although the amplitudes are quite different. At the crest, HVSr computed for explosions

#2 and #3 (from the Northern side of the hill) are quite different from those computed from the records generated by explosions #1 and #4 (from the Southern side). In spite of these differences, average HVSR is similar to average SSR at least from a qualitative point of view. The peaks of SSR discussed in the previous paragraph are also clearly observed in average HVSR. However, the amplitudes of average HVSR are generally larger than those associated to average SSR reaching a maximum value of six for frequencies larger than 20 Hz.

HVSR computed from noise

The ratios between the radial and the vertical component computed from microtremors measurements are shown in Figure 6 for station 1, at the Southern toe, and station 2, at the crest. As mentioned before, more than one hundred 40-sec running time windows were employed and the resulting average \pm one standard deviation is shown for both stations. For comparison, HVSR and SSR estimated from explosion data are also reported. At the toe, a prominent peak at about 12-14 Hz is observed with an amplification factor of about 6. At the crest a rather flat trend is observed with amplification of about 3 for frequencies smaller than 10 Hz and larger than 18 Hz. A minimum value is observed between 12 and 16 Hz. The larger amplifications observed at the toe with respect to the crest are probably due to stratigraphic effects associated to the presence of a sedimentary cover at the toe of the hill. In fact, it is well known that, even for very steep ridges, the variation of amplitude associated to topography can be dominated by effects due to sediments (Pedersen et al., 1994). Our results confirm that it is difficult to obtain good estimates of topographic amplification using SSR because of the lack of good reference stations close to the topographic feature that is investigated. They also underscore the usefulness of methods like the HVSR technique, which do not require a reference station. Average HVSR and SSR from explosions are generally comprised within the standard deviations of Nakamura estimates with the exception of the range 10-15 Hz at the toe and the largest frequencies at the crest.

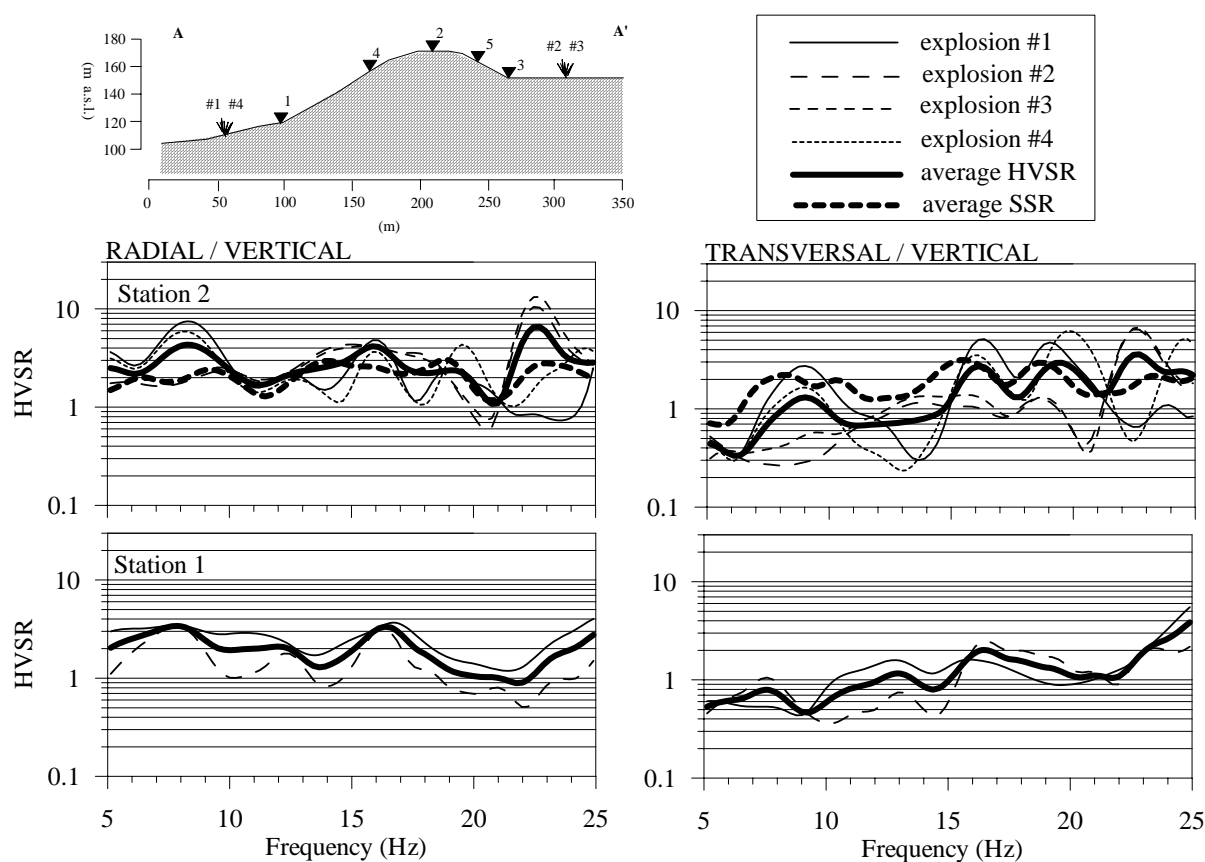


Figure 5. HVSR computed from explosions data at crest (station 2) and at the Southern toe (station 1).

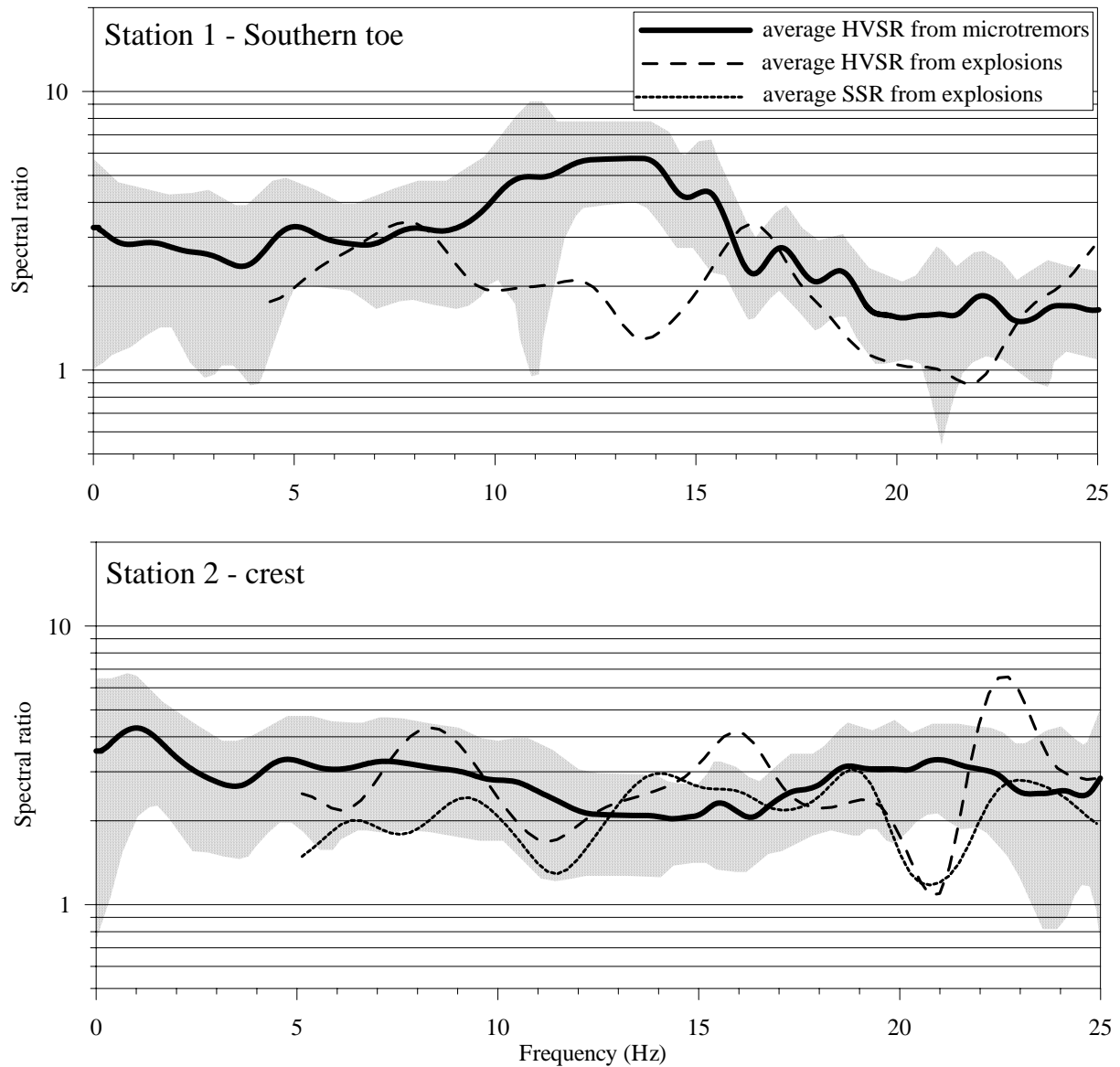


Figure 6. HVSr computed from ambient noise for radial component at stations 1 (Southern toe) and 2 (crest); shaded area: average HVSr \pm 1 standard deviation. For comparison average HVSr from explosions data and average SSR are also shown.

NUMERICAL ANALYSES

We modeled the seismic response of a 2D cross section of the hill. The cross section chosen was that where the instruments were installed (A-A', Figure 1b and 1c). We used the indirect boundary element code BESOIIL (Sanò, 1996). The material was assumed to be homogeneous and linear elastic, and characterized by a shear wave velocity $V_s=1000$ m/s, a Poisson ratio of 0.30 and a unit weight of 23 kN/m^3 . Material damping was considered negligible. Horizontal and vertical transfer functions at the crest were computed assuming incidence of plane SV waves (in-plane motion) as input. The incidence angle was varied in the range from -30° to $+30^\circ$ with respect to vertical. The ratio between horizontal and vertical transfer functions (theoretical HVSr) was computed for all incidence angles.

In Figure 7 horizontal transfer functions and theoretical HVSr are compared for each incidence angle and as average values. A large scatter of the transfer functions, and therefore of the HVSr as a function of incidence angle, can be observed. On average, the horizontal transfer functions show low amplitude amplifications, rather flat in the frequency range analysed. Larger amplitudes are observed

for frequencies lower than 5 Hz and, secondarily, for frequencies higher than 20 Hz while a minimum is reached in the range 11-16 Hz. HVSR shows a higher variability but their average shape is quite similar to that of the average horizontal transfer function, with higher amplifications at low and high frequencies and a minimum in the range 12-16 Hz. From a quantitative point of view, amplification factors derived from computed HVSR are larger than those observed in the horizontal transfer functions.

The similarity between the shape of horizontal transfer functions and HVSR at the crest is, at present, the only theoretical support to the use of HVSR for the qualitative estimate of topographic site effects. A similar result was found by Chávez-García et al. (1996) with numerical analyses carried out on an elongated ridge located in Epire (Northern Greece).

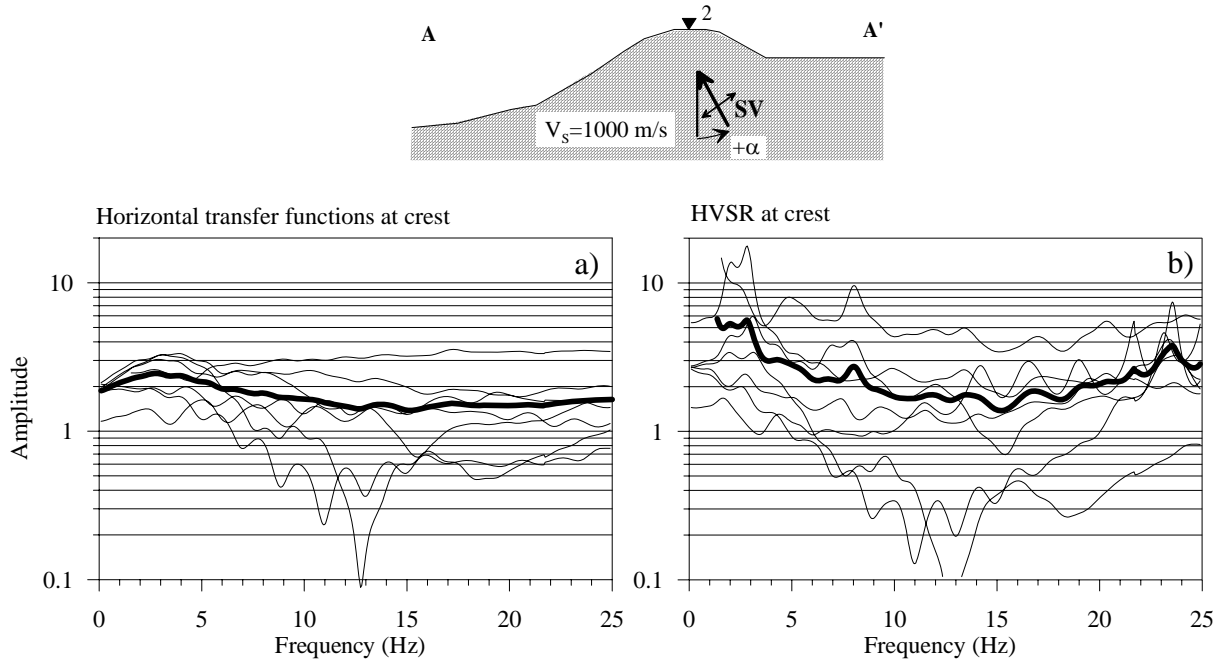


Figure 7. Results of numerical analyses: (a) transfer functions of horizontal component at crest (b) theoretical HVSR at crest; the thin lines refers to each one of the seven different incidence angles ($\alpha = -30^\circ, -20^\circ, -10^\circ, 0^\circ, 10^\circ, 20^\circ, 30^\circ$) of SV waves while the thick line is the average.

COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL HVSR

Theoretical and experimental results at the crest are compared in Figure 8. A good agreement between theoretical HVSR and HVSR from microtremors can be observed, especially in the range 5-20 Hz. A minimum value of amplification is obtained in the range 12-16 Hz while larger amplification values are observed at higher and lower values of frequency. The average of the theoretical HVSR is shifted toward smaller values of amplitude with respect to the experimental curve but is always comprised in the standard deviation range associated to the Nakamura estimates. These quantitative differences may be due to the fact that a bidimensional homogeneous model may be too large a simplification and therefore does not take into account stratigraphic effects related to impedance contrasts in the subsoil and tridimensional effects.

It should be pointed out that HVSR and SSR from explosions show larger variability than experimental and theoretical HVSR. This is probably because the number of events we could generated in the field are not enough to compute a valid average for the transfer functions. For SSR, the uncertainty related to our simplified geometric attenuation correction is also to be considered.

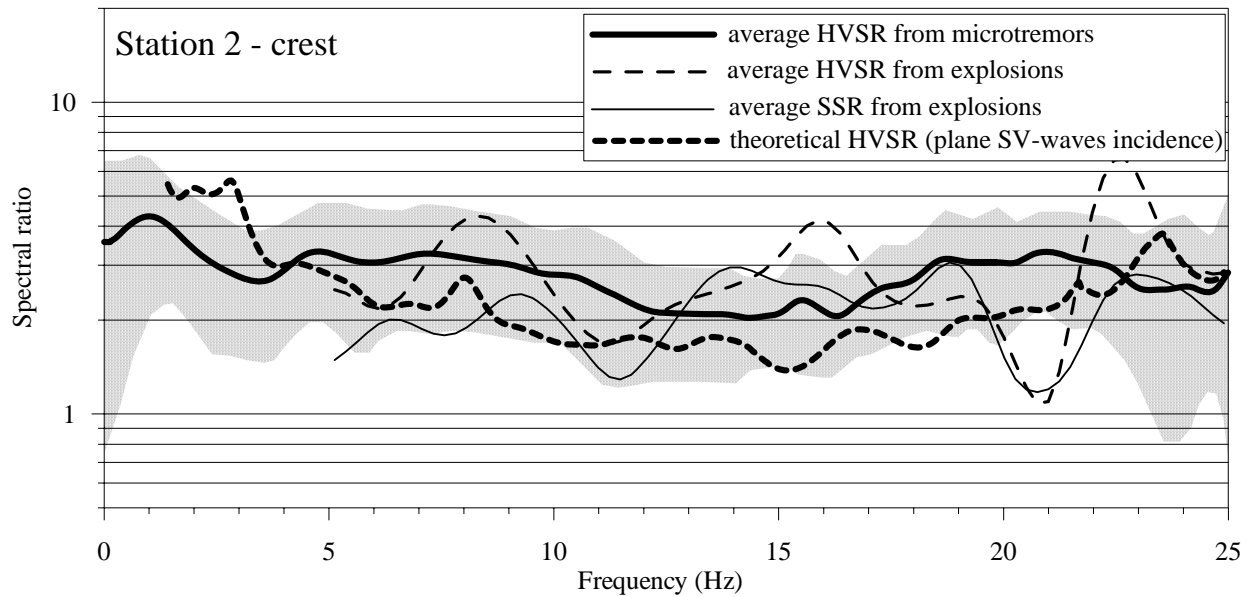


Figure 8. Comparison between theoretical and experimental HVSR for the radial component at the crest; average SSR is also reported; shaded area: average HVSR from microtremors \pm one standard deviation.

CONCLUSIONS

A field experiment was conducted in a rocky hill in Northern Greece in order to study the diffracted wavefield and to record data relevant for the qualitative and quantitative estimate of topographic site effects. Four explosions were generated at the base of the hill and ground motion was recorded along a cross section of the hill. Between the explosions data acquisition continued in order to record ambient noise (microtremors).

First, we used the records to construct seismic sections along the hill in order to study the scattered wavefield. We observed diffracted Rayleigh waves propagating from the crest toward the base of the hill. These diffracted waves increased significantly ground motion duration far from the sources. Then, the experimental data were processed by computing Standard Spectral Ratios (SSR) between the station at the crest and those at the toe and along the flanks. Classical SSR were modified in order to take into account geometric attenuation effects since the distance between the stations is comparable with that between the source and the first station. The location of the hill chosen for the study made it impossible to find an adequate reference station. This is a common problem in the experimental study of topographic site effects. For this reason, horizontal to vertical spectral ratios (HVSR) were also computed using both the explosion data and ambient noise recordings. Our purpose was to explore the applicability of this non-reference technique in estimating topographic effects. Finally, experimental HVSR were compared with theoretical ones, computed by numerical analyses carried out with a bidimensional boundary element computer code on the instrumented cross section of the hill. Plane SV-waves with different incidence angles were assumed as input. A good qualitative agreement between HVSR from microtremors measurements and theoretical HVSR at the crest was found. From a quantitative point of view, experimental amplifications are larger than those computed from the numerical model. Possible explanations for this quantitative disagreement are stratigraphic and tridimensional effects that the 2D homogeneous numerical model does not take into account.

Our results support the use of HVSR to estimate topographic site effects. A good estimate of the horizontal transfer function of a topographic feature may be obtained using HVSR computed even from noise recordings. Although this conclusion needs further studies to be substantiated, HVSR technique may have a large potential to evaluate site effects in a large variety of morphological and geological conditions, without the shortcoming of the SSR technique.

Regarding the theoretical background of HVSr technique, we observed a similar shape between horizontal transfer functions and HVSr derived at the crest by the numerical analyses. Chávez-García et al. (1996) obtained parallel results. These two studies are, at present, the only supporting evidence for the use of HVSr for qualitative estimate of topographic site effects.

Explosions records can be very useful for the study of the wavefield diffracted by the ridge. The careful analysis of the diffracted wavefield gives useful information to determine the mechanical properties of the medium. However, a qualitative and quantitative estimation of amplification factors requires a much larger number of events.

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